

APPARENT OPTICAL PROPERTIES IN WATERS INFLUENCED BY THE MISSISSIPPI RIVER*

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ABSTRACT

In-water downwelling irradiance (E_d) and upwelling radiance (L_u) were measured in coastal waters influenced by the Mississippi River at wavelengths corresponding to SeaWiFS spectral bands in April of 2000. Results of derived apparent optical properties (AOP's) such as spectral diffuse attenuation coefficient for downwelling irradiance (K_d) suggest that they are mainly influenced by phytoplankton chlorophyll. Large variations in chlorophyll concentrations (0.2 to $> 10 \text{ mg m}^{-3}$) correspond to variations in K_d at 443 nm ranging from about 0.1 to $> 1.5 \text{ m}^{-1}$. Attenuation values at 443 nm generally peaked (or were minimal at 555 nm) at depths where chlorophyll concentrations were high. Above water remote sensing reflectance $R_{rs}(443)$ derived from E_d and L_u shows good agreement to surface chlorophyll. Ratios of remote sensing reflectance, $R_{rs}(443)/R_{rs}(555)$ versus chlorophyll suggests a potential for obtaining a suitable bio-optical algorithm for the region influenced by the Mississippi River.

1.0 INTRODUCTION

The Mississippi River ranks sixth in the magnitude of discharge among the world's rivers (Milliman and Meade 1983) and plays an important role in the transport of organic carbon to the Gulf of Mexico. However, due to the complexity of physical, chemical and biological processes in this river impacted system, an accurate characterization of spatial and temporal patterns of particulate and dissolved organic matter distribution presents many difficulties. Ocean color satellite monitoring with new sensors such as SeaWiFS and MODIS provides an opportunity to obtain synoptic estimates of bio-optical constituents (e.g. chlorophyll, phytoplankton productivity, colored dissolved organic matter) necessary to aid the quantification and understanding of organic fluxes in this coastal region.

In open ocean or Case 1 waters, ocean color bio-optical algorithms have been successfully used to estimate bio-optical variables such as chlorophyll concentrations from satellite data (O'Reilly et al. 1998). The co-varying nature of phytoplankton chlorophyll and its degradation products have allowed the development of algorithms directly relating satellite derived ratios of remote sensing reflectance to surface water chlorophyll concentrations. However, in coastal or Case 2 waters this direct relationship may not be applicable as the in water constituents such as chlorophyll, colored dissolved organic matter (CDOM) and suspended sediments may not be correlated (Tassan 1994, Carder 1991). Furthermore, in river impacted systems such as the Mississippi River, these in-water constituents may

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exhibit large spatial and temporal variations as a result of river discharge, bottom resuspension and phytoplankton productivity (Lohrenz et al. 1999). Better knowledge of the bio-optical properties would aid the development of suitable bio-optical algorithms for a coastal region such as that influenced by the Mississippi River.

Apparent optical properties of seawater such as the vertical attenuation coefficient for irradiance, radiance or scalar irradiance are largely determined by the inherent optical properties (e.g. absorption and scattering coefficients) of the aquatic medium (Kirk 1984). The process of light absorption and scattering by the various seawater constituents (e.g. particulate and dissolved organic matter) are described by the inherent optical properties or IOPs. The vertical attenuation coefficient for downwelling irradiance K_d , the subsurface irradiance reflectance R , and other AOPs have been studied as a function of these IOPs (Morel and Prieur 1977; Kirk 1984; Gordon 1989) since generally AOPs are easier to measure. One of the objectives of our study has been to examine the bio-optical properties in the coastal waters influenced by the Mississippi River that would contribute to the understanding and development of a suitable bio-optical algorithm for ocean color remote sensing. We conducted in water measurements of IOPs such as absorption and scattering and obtained estimates of K_d and remote sensing reflectance, R_{rs} using measurements of downwelling irradiance and upwelling radiance. Specifically, we describe and interpret observations of K_d and R_{rs} in relation to absorption and in-water constituents such as chlorophyll and CDOM.

2.0 METHODS AND DATA

A research cruise was undertaken onboard the *R/V Pelican* from 5 to 13 April 2000 where bio-optical measurements were obtained in the Mississippi River plume, the open ocean and the inner Shelf (station locations shown in Figure 1). Although the cruise was conducted during a high river-flow season, the Mississippi River discharge volume as measured at the Tarbert Landing station (located in the Mississippi River) indicated a lower than normal discharge volume for the season. Bio-optical measurements were obtained using an optical profiling package that integrated a number of optical instruments within a metal cage. Discrete water samples were obtained immediately after the bio-optics cast with a rosette sampler equipped with 10-liter Niskin bottles.

The bio-optical package (Figure 2) comprised of sensors for measurements of conductivity and temperature (SBE-19), chlorophyll fluorescence (Wetlabs miniature fluorometer), absorption/attenuation at nine wavebands (ac-9), downwelling spectral irradiance and upwelling spectral radiance at seven channels (Satlantic OCR, OCI-200), and a scattering meter (HOBI Labs). All instruments were positioned vertically in the deployment cage and secured with hose clamps. A data acquisition unit (ac9+) was used to integrate and archive the data collected from the different instruments in the bio-optical package. Subsequently upon transfer of the data to a desktop computer, a separate software program was used to unpack into separate files the data corresponding to individual instruments. A MATLAB program was then used to depth align the data based on time stamps referenced to the CTD depth. All data were then separated into downcast and upcast segments and averaged into 0.5 m or 1 m bins for further processing or analysis.

The ac-9 consists of dual, 25-cm pathlength flow tubes for measurement of absorption (a) and attenuation (c) at nine 10-nm spectral bandwidths (412, 440, 488, 510, 532, 555, 650, 676 and 715 nm). Optically clean water from a Nanopure system was used to calibrate the ac-9 during the cruise. Average values of absorption and attenuation coefficients obtained during the calibration were then subtracted from in situ measurements. Software was further written to implement three additional corrections (temperature, salinity and scattering) to the ac-9 data (Pegau et al. 1997; Zaneveld and

Moore 1994). The ac-9 data was generally binned at 1-m depth intervals, but at stations with shallow depths, binning was set to 0.5 m.

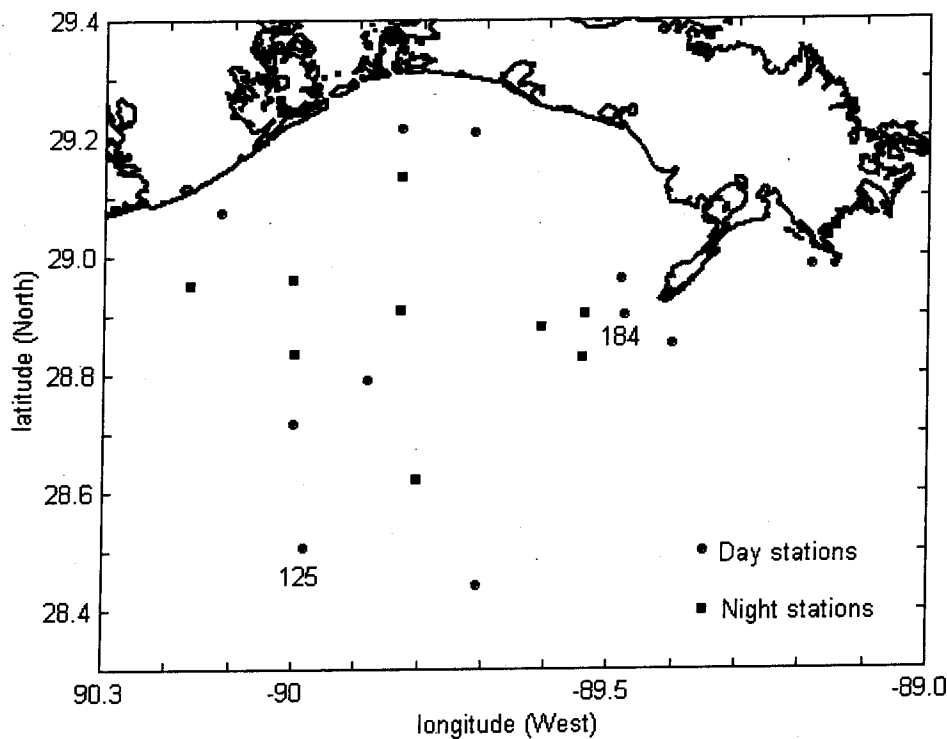


Figure 1. Map showing location of stations sampled during a cruise in the Mississippi River Bight between 5-13 April 2000. Observations from the two numbered stations (125, and 184) are discussed in detail.

Spectral downwelling irradiance $E_d(\lambda)$ and upwelling radiance $L_u(\lambda)$ profiles were processed to calculate the diffuse attenuation coefficients $K_d(\lambda)$ and $K_u(\lambda)$. These coefficients were determined as the slope of $\ln E_d(\lambda)$ or $L_u(\lambda)$ versus depth. An 11-point moving linear regression of $\ln E_d(\lambda)$ and $\ln L_u(\lambda)$ versus depth were used to obtain vertical profiles of $K_d(\lambda)$ and $K_u(\lambda)$. Values of $K_d(\lambda)$ and $K_u(\lambda)$ at the shallowest depth were then used to estimate $E_d(\lambda, 0^-)$ and $L_u(\lambda, 0^-)$ just beneath the sea surface. Based on known values of Fresnel reflectance at the water-air interface for upwelling radiance and downwelling irradiance, the sub-surface values $E_d(\lambda, 0^-)$ and $L_u(\lambda, 0^-)$ were extrapolated to values just above the sea surface. Remote sensing reflectance $R_{rs}(\lambda, 0^+)$ was then calculated as

$$R_{rs}(\lambda, 0^+) = L_u(\lambda, 0^+) / E_d(\lambda, 0^+) \quad (1)$$

where $L_u(\lambda, 0^+)$ is the water-leaving radiance measured in the nadir direction just above the sea surface and $E_d(\lambda, 0^+)$ is the downwelling irradiance incident on the sea surface.

Water samples at discrete depths were collected using a CTD rosette multi-bottle array system (General Oceanics Model 1015-12). Water samples collected from CTD casts immediately prior to or

following optical profiles were used for better correlation with optical measurements. Discrete samples were processed for the following: 1) chlorophyll and phaeopigments using HPLC and fluorometric methods, 2) particulate absorption ($a_{ph}(\lambda)$ and $a_d(\lambda)$) using QFT method, and 3) CDOM absorption $a_g(\lambda)$ using a multiple pathlength capillary waveguide (Miller et al. 2002).

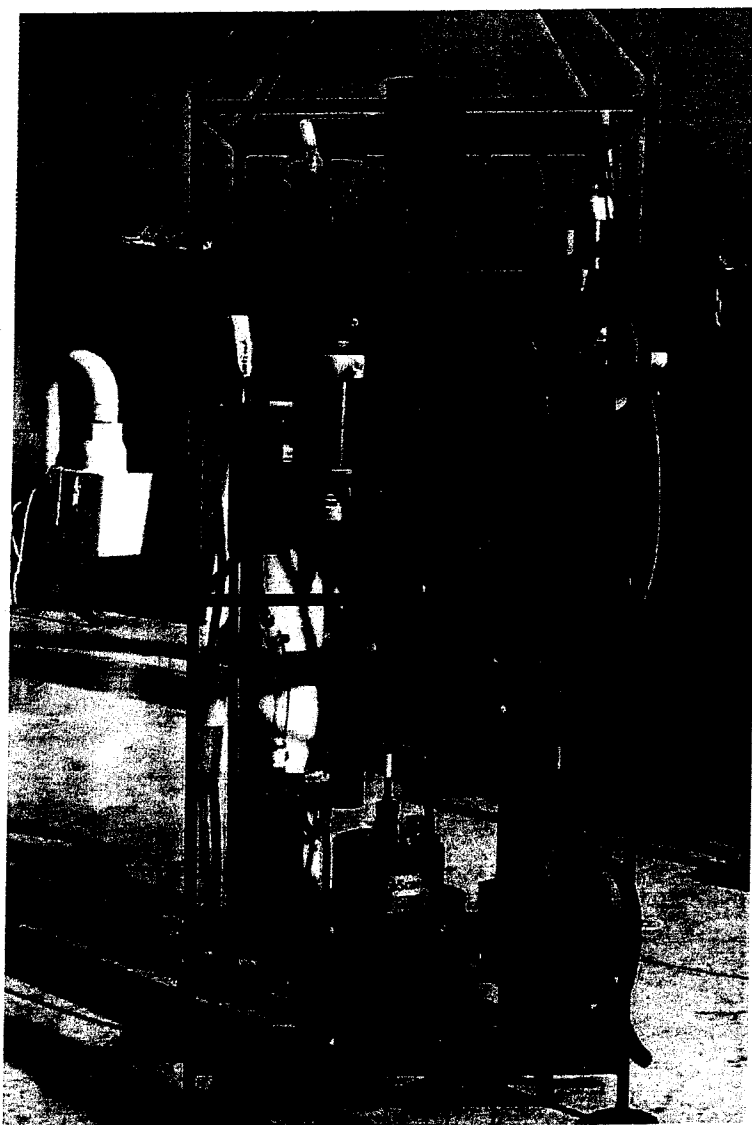


Figure 2. The bio-optical package shown assembled and ready for deployment aboard the *R/V Pelican*. The instruments on the bio-optical package include: a Seabird CTD (SBE-19), a Wetlabs miniature fluorometer, ac-9 spectral attenuation/absorption meter, Satlantic radiometers (OCI-200, for downwelling irradiance and OCR-200, for upwelling radiance), and a scattering meter (Hydroscat-2 from HOBI Labs).

3.0 RESULTS AND DISCUSSION

The study area comprised waters with highly variable physical, biological and optical properties. Physical properties (temperature and salinity) at two representative stations (stations 125 and 184, Figure 1) associated with river end members indicates predominant influence of the Mississippi River (station 184) and the open Gulf of Mexico waters (station 125). As was typical at most other stations, a stratified water column with decreasing gradient in the salinity field revealed the extent of spread and mixing of the Mississippi River plume. High near surface chlorophyll concentrations at station 184 that was located near the Southwest Pass ($\sim 10 \text{ mg m}^{-3}$) were associated with the low salinity surface waters. Chlorophyll concentrations at this station decreased with depth and increasing salinity. Vertical profiles of total absorption at this station (Figure 4) clearly shows that the total absorption coefficient follows the vertical chlorophyll distribution. Surface CDOM absorption values of $\sim 0.3 \text{ m}^{-1}$ (440 nm) measured at a neighboring station indicates that at station 184 the near surface total absorption of $\sim 1.2 \text{ m}^{-1}$ (at 440 nm) was mainly due to phytoplankton chlorophyll. Vertical profiles of K_d at 412, 443 and 555 nm at station 184 (Figure 5) appear to also closely follow the chlorophyll and absorption profiles. High K_d values of $\sim 1.8 \text{ m}^{-1}$ at a depth corresponding to the chlorophyll maximum strongly suggests a direct correlation between K_d and chlorophyll. K_d at the longer wavelength of 555 nm was minimal at near surface waters and was higher at depths where chlorophyll concentrations were lower. High K_d values suggest that light would be rapidly attenuated in these waters and would thus limit phytoplankton production to surface waters.

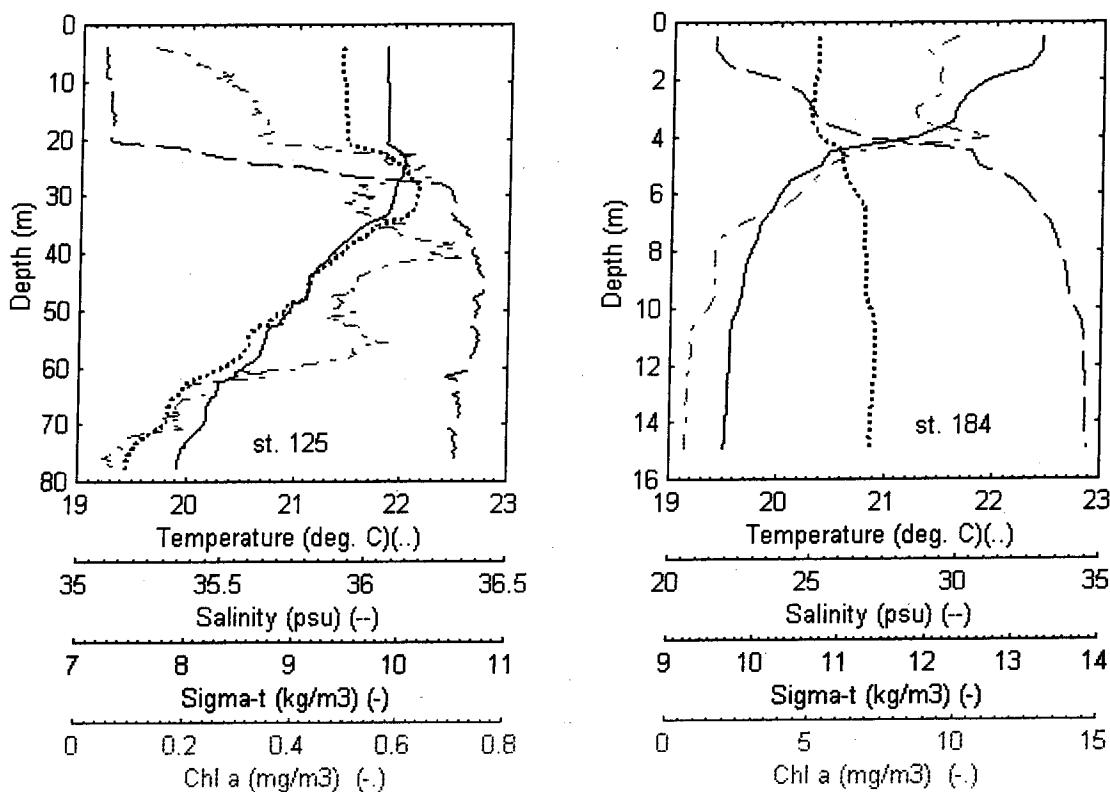


Figure 3. Vertical profiles of temperature, salinity, sigma-t, and chlorophyll at stations 125 (open ocean) and 184 (near Southwest Pass).

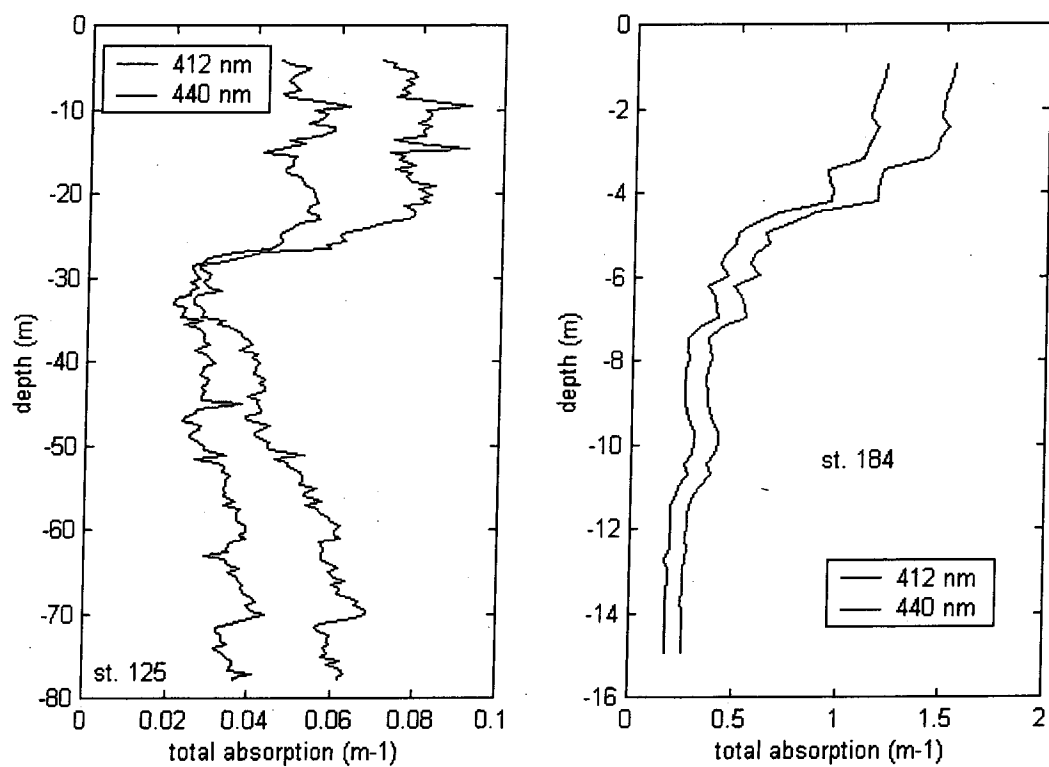


Figure 4. Profiles of total absorption coefficients at 412 and 440 nm (m^{-1}) for stations 125 and 184.

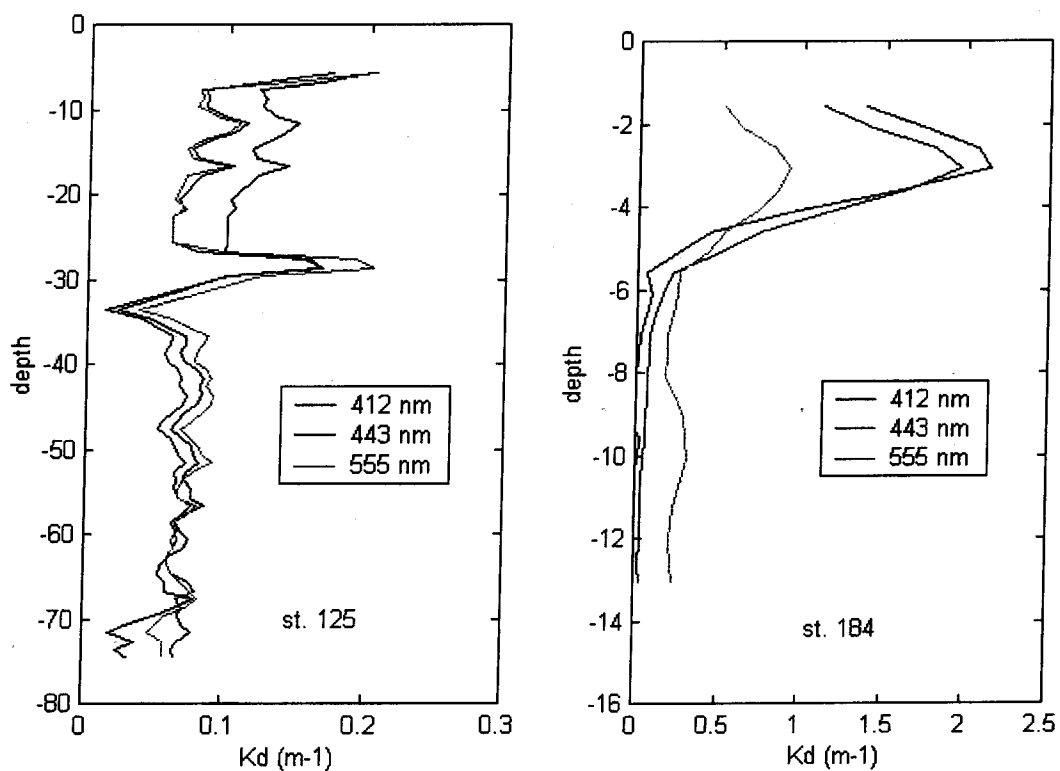


Figure 5. K_d spectral profiles at 412, 443 and 555 nm for stations 125 and 184.

In contrast, chlorophyll concentrations at station 125 were much lower and varied from ~ 0.2 to 0.6 mg m^{-3} across the water column. At this station there appeared to be a well-mixed surface layer with salinity of 35.1 psu (0-20 m depth) over more saline deeper waters (36.4 psu). There was not much structure in the total absorption profiles at this station being quite uniform with an average value of about 0.04 m^{-1} . In addition to chlorophyll, CDOM and detrital particles may have contributed to the absorption field, resulting in a profile that could not be directly associated with chlorophyll distribution. This pattern of vertical profiles were reflected in the K_d profiles which were also very low (average value of about 0.1 m^{-1}) and uniform with depth. However, surface waves appeared to affect K_d estimates even at depths up to 30 m.

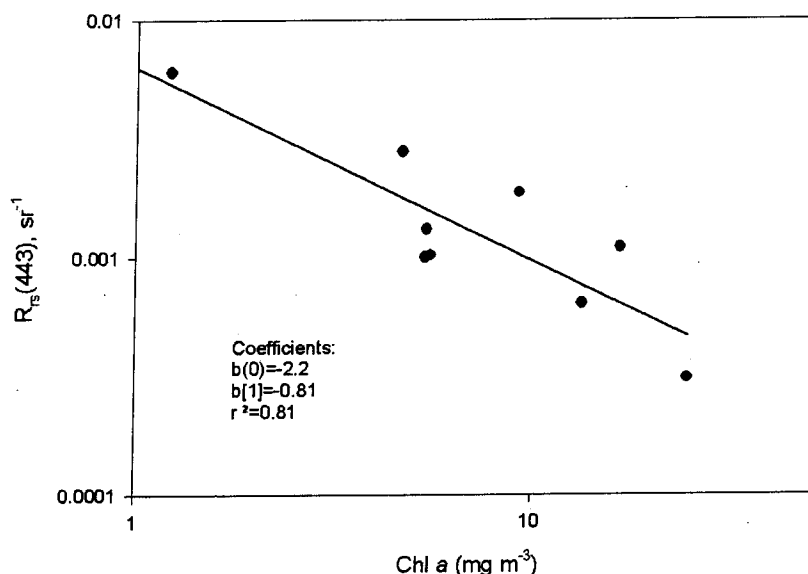


Figure 6. In water derived $R_{rs}(443)$ versus surface chlorophyll for plume and coastal stations in waters influenced by the Mississippi River.

In-water derived remote sensing reflectance $R_{rs}(443)$ versus surface chlorophyll (Figure 6) shows a high level of linear correlation between the two variables, with $R_{rs}(443)$ decreasing with increasing chlorophyll concentrations. Empirical algorithms, such as the ocean color OC2 and OC4 algorithms (O'Reilly et al. 1998) use blue to green ratio of remote sensing reflectances to estimate chlorophyll concentrations from atmospherically corrected satellite remote sensing signal. Initial results reported from this cruise (Miller and D'Sa 2002) indicate possibility of establishing separate relationships between ratios of reflectances, $R_{rs}(490) / R_{rs}(555)$ and chlorophyll and $R_{rs}(510) / R_{rs}(555)$ and CDOM absorption. A seasonal and multi-year suite of measurements will help define coefficients for these algorithms.

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